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NBS TECHNICAL NOTE 569

Hurricane Camille-August 1969

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Hurricane Camille - August 1969

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PREFACE

One week after Hurricane Camille struck the Mississippi-Louisiana Gulf Coast, a four-man team from the Building Research Division of the National Bureau of Standards was sent to investigate the damage to buildings and other structures. The team members were:

Dr. Edward O. Pfrang, Chief, Structures Section

Mr. William C. Cullen, Chief, Materials Durability and Analysis Section

Mr. Robert D. Dikkers, Structural Research Engineer

Dr. Richard D. Marshall, Structural Research Engineer

The team carried out photographic surveys on the ground and from the air during the period of August 24-26, 1969. The investigation was primarily limited to the heavily damaged area along the coast from Waveland to Biloxi, Mississippi. This report is based largely on the photographic data acquired during this period and on wind and surge data compiled by Mr. H.C.S. Thom, Senior Research Fellow, Environmental Data Service, NOAA. Additional information was provided by other agencies and individuals and their assistance is acknowledged in this report.

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Along the Mississippi Gulf Coast

by

Robert D. Dikkers, Richard D. Marshall

and H.C.S. Thom

ABSTRACT

One week after Hurricane Camille devastated the Mississippi-Louisiana Gulf Coast with 125 mph winds and 20-ft tides on August 17, 1969, a four-man NBS team investigated the damage to buildings and other structures. This report presents photographic survey data from this investigation along with additional data on wind speeds and storm surge. Based on these data, suggestions are made pertaining to the improvement of building design and construction practices.

Key words: Buildings; failure; hurricanes; mobile homes; roofs; structural engineering; tides; wind.

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* This investigation was conducted with the aid of a financial grant from the Office of Civil Defense, Office of the Secretary of the Army.

INTRODUCTION

Hurricane Camille (August 1969) was one of the most intense and costly tropical storms ever to hit the United States mainland. It devastated the Mississippi-Louisiana Gulf Coast with high winds and tides and then in a weakened condition dumped torrential rains over Virginia's Blue Ridge Mountains, causing flash floods and landslides. Camille caused a total of 248 deaths and $1.42 billion in property damage along the Mississippi-Louisiana Gulf Coast and in Virginia [1, 2, 3].*

In Mississippi-Louisiana, 144 persons were killed and 8,931 injured. The total dollar damage was about $1.28 billion. Hurricane Betsy which struck the Louisiana coast in September, 1965, caused less than 100 deaths and approximately $1.76 billion damage in terms of 1969 dollars.

Based on Red Cross survey data [3], the impact of Hurricane Camille on property in Mississippi-Louisiana is summarized below:

5,662 homes destroyed
13,915 homes with major damage
33,933 homes with minor damage
1,082 mobile homes destroyed
621 mobile homes with major damage
775 farm buildings destroyed
2,289 farm buildings with major damage
679 small businesses destroyed or with major damage

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* Figures in brackets refer to the references listed at the end of this report.

Path of Hurricane

Shortly before 8 A.M. CDT on Friday, August 15, 1969, a reconnaissance aircraft located Hurricane Camille about 75 miles from extreme southwestern Cuba [4]. Highest winds were estimated at 90 mph. The storm had been under close surveillance for the previous 24 hours when winds were still less than 60 mph near the center of the depression. During the next two days Camille continued moving toward the north northwest at about 10 mph. The hurricane path is indicated in figure 1.

At 1 P.M. CDT on Sunday, August 17, Camille was 155 miles southeast of New Orleans and moving north northwest at 12 to 15 mph. Maximum wind speeds were estimated at 160 mph near the center. Camille passed just to the east of the mouth of the Mississippi River generating a surge that topped both east and west bank levees and caused severe flooding in Plaquemines Parish, Louisiana. The center of Camille came ashore at Waveland, Mississippi, at 10:30 P.M. CDT and passed over Bay St. Louis on her way north through Hancock County. During the early morning hours the hurricane began to weaken, and at 5 A.M. CDT on Monday, August 18, Camille was located about 40 miles south southeast of Jackson, Mississippi, moving northward at about 15 mph. She continued to weaken as she moved northward through Mississippi and was classified as a depression on moving into Tennessee. Rainfall over southern Mississippi and southeastern Louisiana ranged from 3 to 11 inches. On Tuesday, August 19, the depression stages of Camille moved into southwestern Virginia and produced torrential rains along the eastern slopes of the

Figure 1. Path of Hurricane Camille.

Blue Ridge Mountains. Rainfall amounts in excess of 25 inches were recorded, producing record flooding along the James River. On August 22, Camille was absorbed into a cold front southeast of Cape Race, Newfoundland.

Wind Regime

In most extreme storm conditions it is difficult to obtain reliable wind speed observations and Hurricane Camille was no exception. Of the wind speed observations taken during the storm [4], approximately six could be considered to be reasonably reliable. These observations were modified to obtain fastest mile speeds at the standard height of 30 ft.

The map of figure 2 is a modification of a map issued by the New Orleans Weather Bureau Office shortly after the passage of Camille. The best estimates of the path and isotachs are shown along with observations of maximum speeds made by commissioned weather observers in the area. Also shown is the calm center or "eye" of the hurricane which was estimated to be approximately 10 miles in diameter as she came ashore.

Two of the most useful observations in setting the general level of the wind were the observation at Keesler Air Force Base and a record from Transworld Drilling Company's Rig 50. The Keesler record is a standard one and required only that the observation be raised from 13 to 30 ft. A reproduction of the Transworld record was first published by DeAngelis and Nelson [4] and is of particular interest because of its proximity to the hurricane center. The record showed a maximum wind speed of 172 mph,

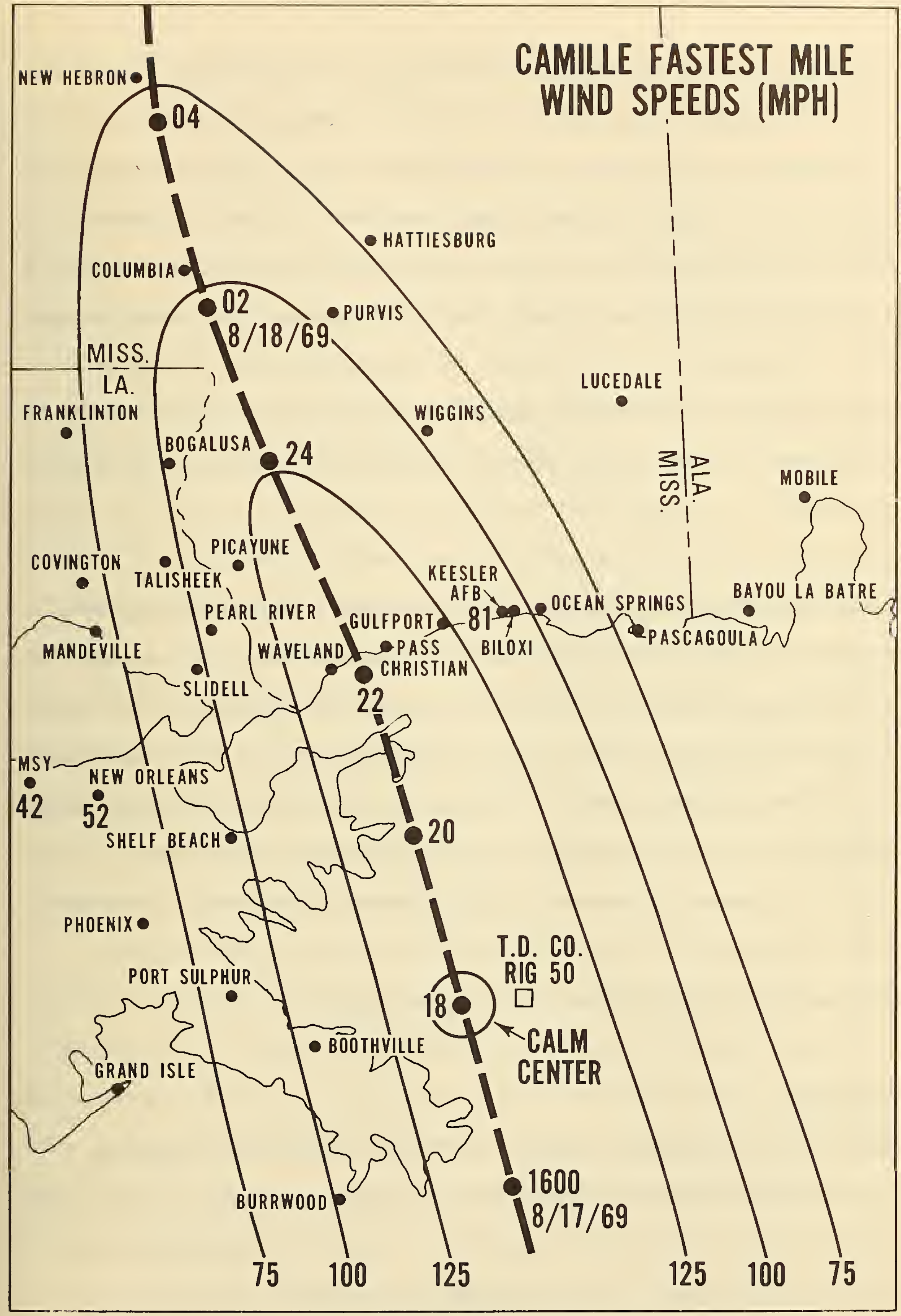


Figure 2. Fastest mile wind speeds (mph) - Hurricane Camille.

but there was some difficulty with the paper transport which caused a time displacement. However, it is not likely that this would have altered the pen displacement. The aneomometer was a propeller-vane type with a distance constant of approximately 15 ft and was mounted about 100 ft above the water [5]. The 172 mph peak speed was reduced to the 30 ft level using a power law approximation of the velocity profile. An exponent of 1/7 was used which appeared to be reasonable considering the condition of the water surface. This resulted in a peak gust of 144 mph and a fastest mile speed of 115 mph at the 30 ft elevation.

Examination of figure 2 shows that the 50-year design winds [6] were exceeded in the area between Slidell, Louisiana, and Ocean Springs, Mississippi. Between Gulfport and Waveland, Mississippi, the 100-year design winds were exceeded by winds corresponding to a mean recurrence interval of perhaps as much as 200 years. Although there were no known official reports of tornadoes, several non-commissioned weather observers reported tornadoes to the northeast of the center where they would be expected to occur. At least one structure (near Wiggins, Mississippi) suggested damage by a tornado [7].

Storm Surge

Major flooding occurred along the Gulf Coast from lower Plaquemines Parish in Louisiana to Bayou La Batre, Alabama, and tides ran 3 to 5 ft above normal as far east as Apalachicola, Florida. Flooding and wave damage were extremely heavy just east of the storm's center where tides

ran as much as 25 ft above mean sea level. Figure 3, reproduced from Geological Survey Maps [8], shows the flooded areas along the Mississippi Coast and the surge height in feet above mean sea level. The isotachs of figure 2 have been superimposed on figure 3 for relating the flood damage to the wind distribution. It should be noted, however, that factors other than wind speed can also influence surge intensity.

In order to give an estimate of the severity of the storm surge, a mixed Fréchet distribution [9] was fitted to the 77-year tide height series at Biloxi. The mixture consisted of two components; tides associated with tropical storms passing to the west of Biloxi and tides associated with all other storm passages. The distributions are shown in figure 4 with the middle curve corresponding to the mixed distribution. The surge height of 15.5 ft recorded at Biloxi corresponds to a mean recurrence interval of 160 years. This is in rough agreement with the mean recurrence interval associated with wind speeds observed in the Biloxi-Gulfport area. Unfortunately, no long-term records are available for surge at Pass Christian where the peak value was observed.

As with all coastal hurricanes, much of the damage from Camille was due to storm surge. In the area extending from Gulfport to Pass Christian, heavy damage due to surge was observed up to 400 yds inland. The intensity of damage was strongly influenced by local topography, there being areas near the peak surge which escaped damage because of slightly higher ground elevation.

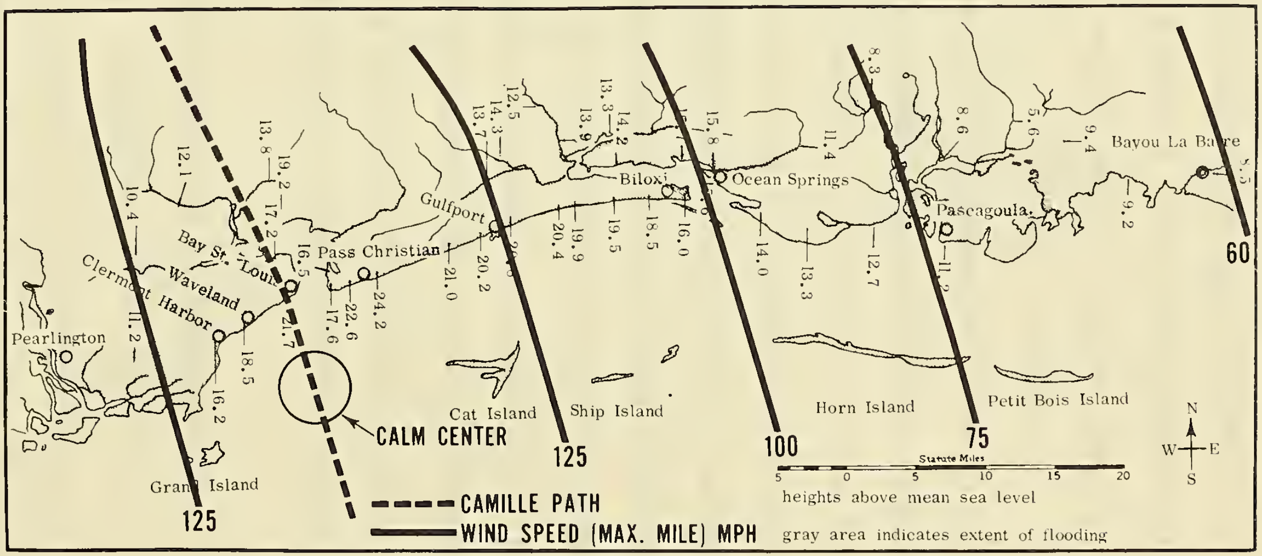


Figure 3. Surge heights and isotachs - Mississippi Gulf Coast.

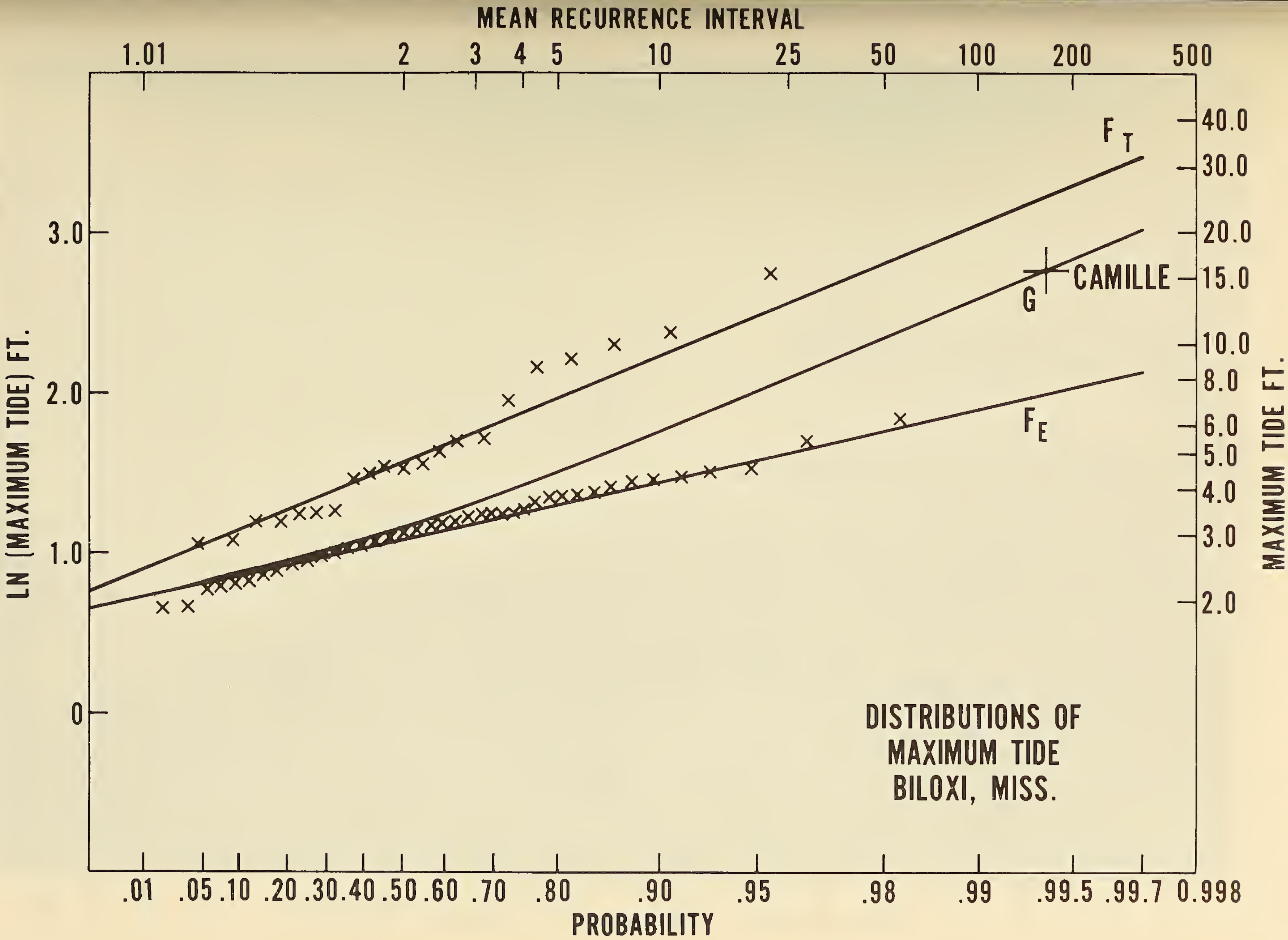


Figure 4. Distribtuions of maximum tide, Biloxi, Mississippi.

STRUCTURAL DAMAGE

The degree of wind damage along the Mississippi Gulf Coast ranged from superficial to total destruction. Damage caused by surge was particularly heavy west of Gulfport and considerable flooding occurred in the back bay areas. The photographs on the following pages illustrate the type and intensity of damage observed by the survey team and are presented in general geographical order, starting at Biloxi and progressing westward to Waveland and then inland for a distance of about 20 miles. A map of the area bounded by Ocean Springs and Bay St. Louis is presented in figure 5.

Biloxi

As indicated in figure 3, maximum wind speeds and surge heights in the Biloxi area were approximately 105 mph and 18 ft respectively. Precast concrete deck slabs of the Biloxi Bay Bridge (fig. 6) were moved longitudinally on their pile bents by surge-borne waves. Some slabs were displaced as much as 3 to 4 ft and considerable debris was lodged in the bridge railing. The ground floor of the Buena Vista Motel (fig. 7) was completely gutted by waves and extensive wind damage to the roofing was observed. Note the proximity of the structure to the water.

Structures on slightly higher ground fared much better even though their ground floors and basements were flooded (fig. 8). Generally, surge damage was limited to those areas within two blocks of the beach.

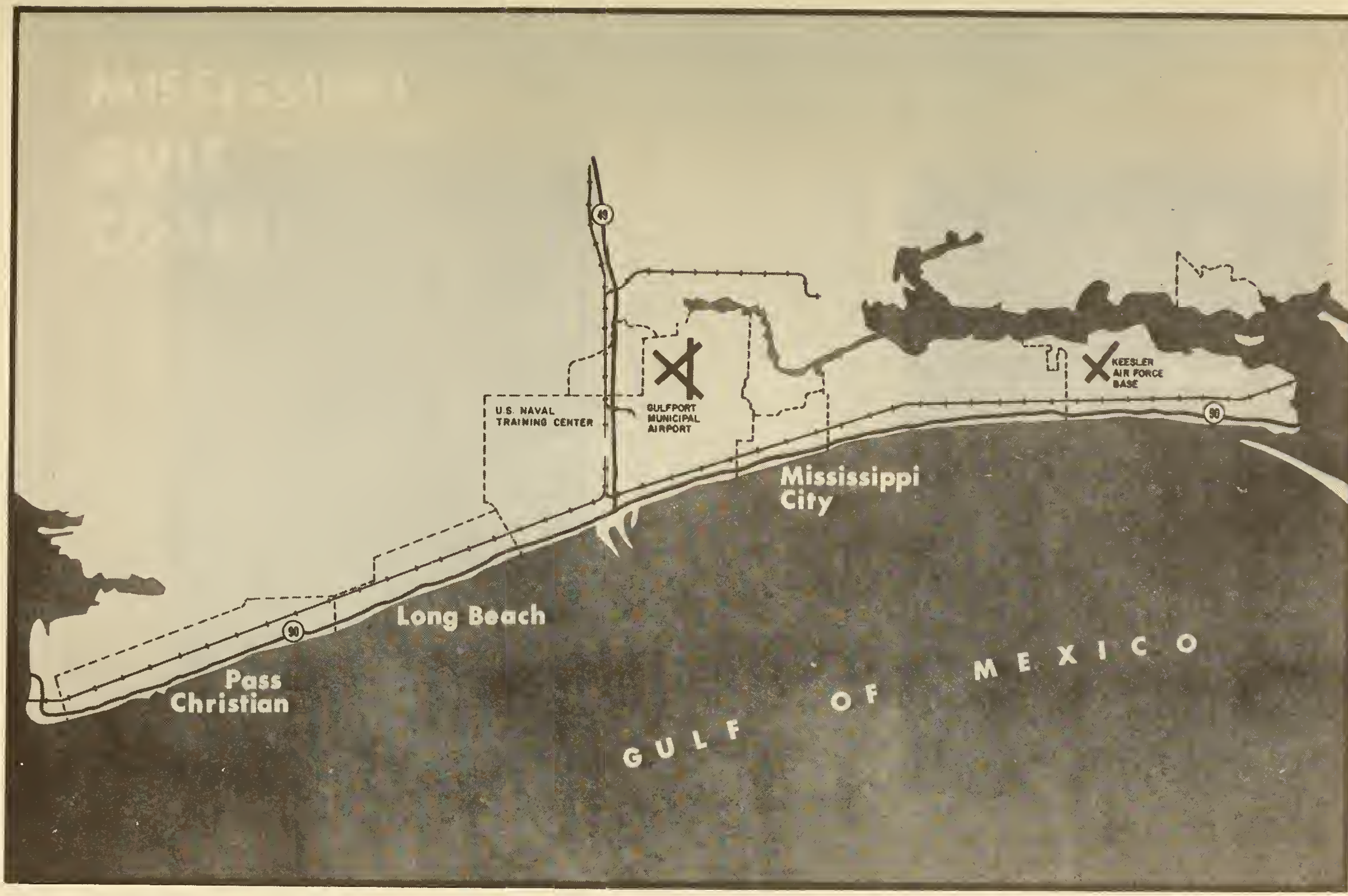


Figure 5. Map of area covered by NBS survey team.

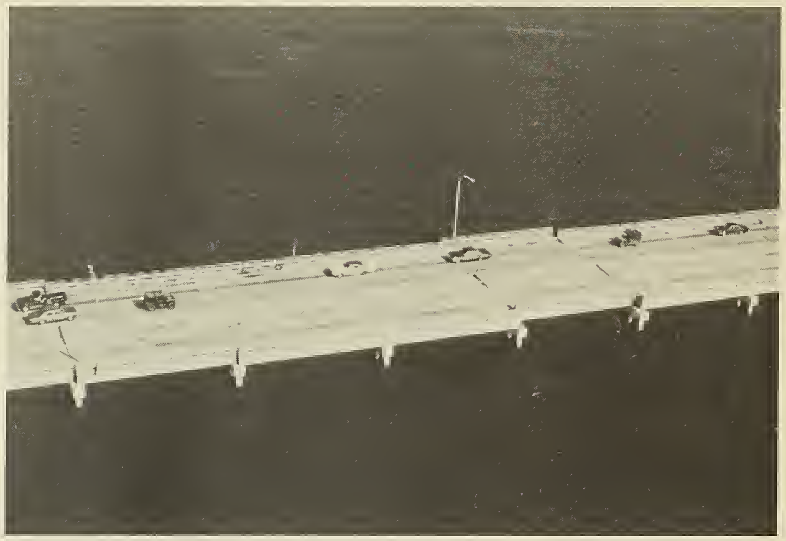


Figure 6. Biloxi Bay Bridge, Biloxi, Mississippi.

Figure 7. Buena Vista Motel, Biloxi.

Figure 8. Coastal area, Biloxi, Mississippi.

Figure 9. Chapel, Keesler Air Force Base, Biloxi.

Keesler Air Force Base - Damage to buildings was limited to loss of cladding and roofing with some flooding occurring in housing developments located along the back bay. The chapel shown in figure 9 suffered the most serious damage with the loss of copper roofing and subsequent water damage to the interior furnishings. Single-family dwellings with wind-resistant shingles exhibited very little damage (fig. 10).

Broadwater Beach Marina - This marina (fig. 11) near Biloxi consists of reinforced concrete columns and double-T roof members over the boat slips. Although some of the roof members were damaged (fig. 12), the overall performance of the structure was very good considering that it was completely inundated by the storm surge. Surge height in this area (approximately half way between Biloxi and Gulfport) was about 20 ft.

The building shown in figure 13 suffered heavy damage due to wave action and wind. Note the damage to roofing near the windward corner of the building. This type of damage is typical of flat-roofed structures investigated by the team. Although the seawall generally suffered light damage, considerable erosion was observed behind the wall and under the adjacent pavement slabs of U.S. 90 as indicated in figure 14.

Gulfport

An aerial view showing a portion of the downtown business and commercial area of Gulfport is shown in figure 15. Many small buildings located along this flat coastal area were heavily damaged or destroyed by the

Figure 10. Single-family residence, Keesler Air Force Base.

Figure 11. Broadwater Beach Marina between Biloxi and Gulfport, Mississippi.

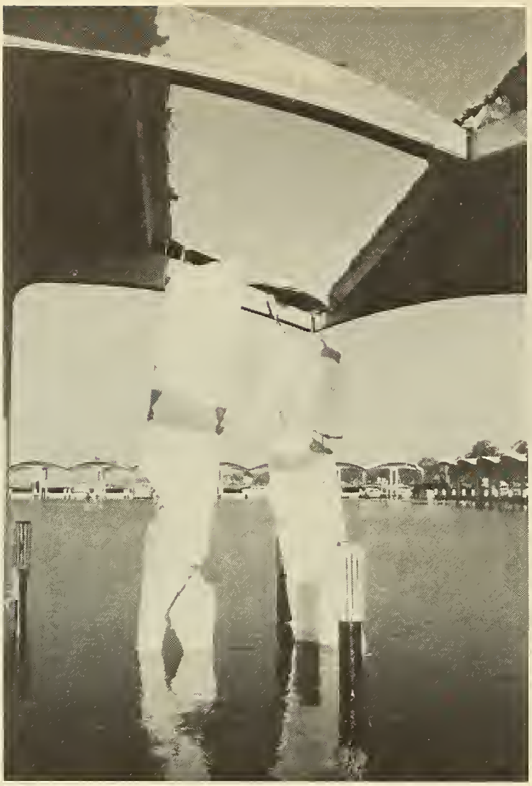


Figure 12. Close-up view of damage to Broadwater Beach Marina.

Figure 13. Residential area between Biloxi and Gulfport, Mississippi.

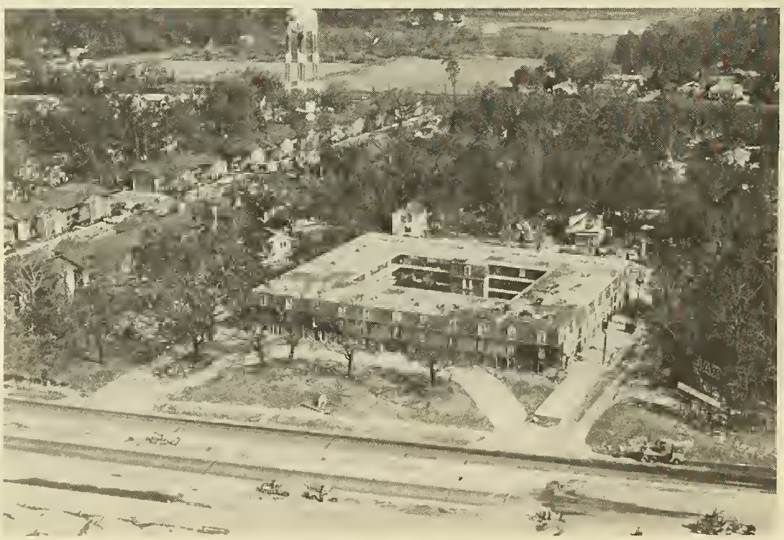


Figure 14. Seawall along U.S. Highway 90.

Figure 15. Business and commercial area, Gulfport, Mississippi.

20-ft storm surge. One group of buildings in this area comprised the Marine Life Aquarium (fig. 16). The large steel-arched building at the left provided shelter for a display tank and a concrete seating area. Detailed description of the damage to these structures has been reported by another survey team [10].

Three large ships, which were driven aground on the Gulfport Coast near the Mississippi Power Company building, are shown in figure 17.

The effect of building geometry on local wind pressures is demonstrated by the church in figure 18. This structure is located approximately 3 miles inland and probably experienced peak gusts when the wind was blowing from left to right. Strong vortex flows can develop along the eaves of the gable end, resulting in extremely high suctions. Failure of this roof structure is quite similar to that depicted in figure 9.

Mississippi Power Company - The new seven-story Mississippi Power Company building is located on U.S. Highway 90 in Gulfport. Figure 19 is an aerial view illustrating the proximity of the building to the coastline. Opened in April, 1969, this $2.5 million concrete frame building sustained only minor damage. To help protect the building from flooding, it was situated on an elevated, earth-banked plaza-podium (about 26 ft above mean sea level).

On the first floor, the building has 35 windows measuring 5 ft by 14 ft and a total of 504 windows, each 5 ft by 8 ft by 6 in, on the second

Figure 16. Marine Life Aquarium, Gulfport.

Figure 17. Ships aground at Gulfport, Mississippi.

Figure 18. Church located in northern part of Gulfport.

Figure 19. Seven-story Mississippi Power Company building, Gulfport, Mississippi.

through seventh floors (fig. 20) [11]. The large first-floor windows were protected from flying or floating debris by a wire fabric screen which was erected just prior to the storm. The windows consist of one-inch thick panels of insulating reflective glass set in bronze anodized aluminum framing with neoprene gaskets. The neoprene gaskets provide a resilient mounting for the glass and prevented metal-to-glass contact and minimized breakage. After the storm, it was reported that, out of more than 500 windows, a total of 13 lights had to be replaced [11].

In addition to the window damage, some minor damage occurred to one side of the roof enclosure surrounding the air-conditioning cooling tower (fig. 21). The structure for the enclosure consisted of rectangular structural steel tubing and 2-in thick concrete panels which were reinforced with expanded metal lath.

Figures 22 through 24 indicate the general level of damage in the area surrounding the Mississippi Power Company. The prefabricated metal building in figure 22 again points up the importance of local wind effects when designing roof elements. The random distribution of damage shown in figure 23 is typical of the entire area covered by the survey. Failures of roofing are usually progressive as is indicated in figure 24. Gravel from this built-up roof contributed considerably to the flying debris.

Figure 20. Close-up view of Mississippi Power Company building.

Figure 21. Enclosure structure on roof of Mississippi Power Company building, Gulfport, MIssissippi.

Figure 22. Area directly north of Mississippi Power Company building.

Figure 23. Area directly east of Mississippi Power Company building, Gulfport, Mississippi.

Wooden frame houses suffered relatively little wind damage, most damage being caused by wind-driven missiles and falling trees. The house shown in figure 25 was subjected to the direct action of waves and was probably battered by water-borne debris. The oil storage tank in figure 26 was carried inland on the surge from its original location on a pier in the port complex. The large dent indicates a collision with other structures while being driven ashore.

An old wood-frame house (fig. 27) escaped major damage except for its metal roof covering.

A major task throughout all the damaged area (Biloxi to Waveland) was the clearing of debris (trees, building materials, etc) from public and private property (fig. 28). Within one week, all major access roads had been opened. It was also reported that in the first two weeks 338 miles of streets had been cleared and an initial 17,000 truckloads of debris dumped [12]. Over a 3-month period more than 300,000 loads were trucked to 17 emergency dump sites.

U.S. Naval Construction Battalion Center - The U.S. Naval Construction Battalion Center in Gulfport is located about 1-1/2 miles inland. Accordingly, structural damage which was observed resulted from high wind forces, not high tides. It was reported that about 10 warehouses, 17 barracks, and 8 miscellaneous structures were either totally destroyed or considered to be beyond repair. Another 23 structures suffered minor damage [13].

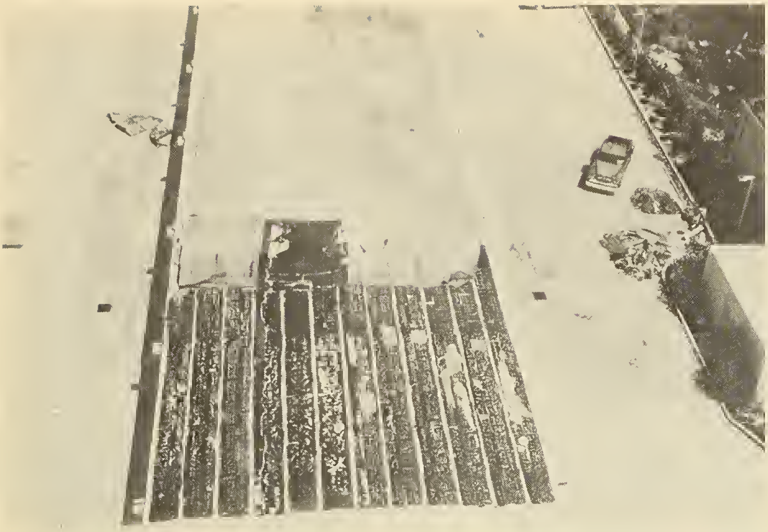


Figure 24. Roofing damage on building adjacent to north side of Mississippi Power Company building.

Figure 25. Wood-frame residence damaged by waves, Gulfport, Mississippi.

Figure 26. Tank washed ashore by storm surge, Gulfport.

Figure 27. Metal roofing damage, Gulfport, Mississippi.

Figure 28. Debris clearance, Gulfport.

Figure 29. Damaged warehouses, U.S. Naval Construction Battalion Center, Gulfport, Mississippi.

An aerial view of the damaged warehouses is shown in figure 29. These wood-frame buildings were built during World War II and were still in daily use. The major damage to these structures occurred on the windward side. As shown in figure 29, the warehouse units were constructed with brick fire walls between each section. The roofs were supported by timber trusses and the front and back walls were of wood-frame construction. Close-up views illustrating the collapsed wood-frame walls, damaged brick fire walls and dislodged roof trusses are shown in figures 30 and 31.

Comparatively minor damage was suffered by three reinforced concrete-masonry warehouses (fig. 32) which were built during or since 1950. These warehouses were located near the older wood-frame warehouses (see upper left of fig. 29). As shown in figure 33, these structures lost some 2-ft wide by 8-ft long precast concrete roof panels along the perimeter of the roof. It was observed that all roof panels were securely anchored at interior points by steel clips but no anchorage was provided for the perimeter panels, the location where peak uplift usually occurs. Prior to the passage of Hurricane Camille, it was reported to the NBS survey team that hundreds of civilian dependents left their homes to take refuge in these concrete-masonry warehouses.

Severely damaged two-story wood-frame barracks and a one-story wood-frame warehouse are illustrated in figures 34 and 35. The type of damage observed from both the ground and the air seems to indicate this area was probably struck by tornadoes. Nearby, large pine trees were

Figure 30. Close-up view of damaged warehouse shown in figure 29.

Figure 31. Damaged warehouse roof and fire wall, U.S. Naval C. B. Center, Gulfport, Mississippi.

Figure 32. Reinforced concrete and masonry warehouse, U.S. Naval C. B. Center, Gulfport.

Figure 33. Precast concrete roof slabs, U.S. Naval C. B. Center warehouses, Gulfport, Mississippi.

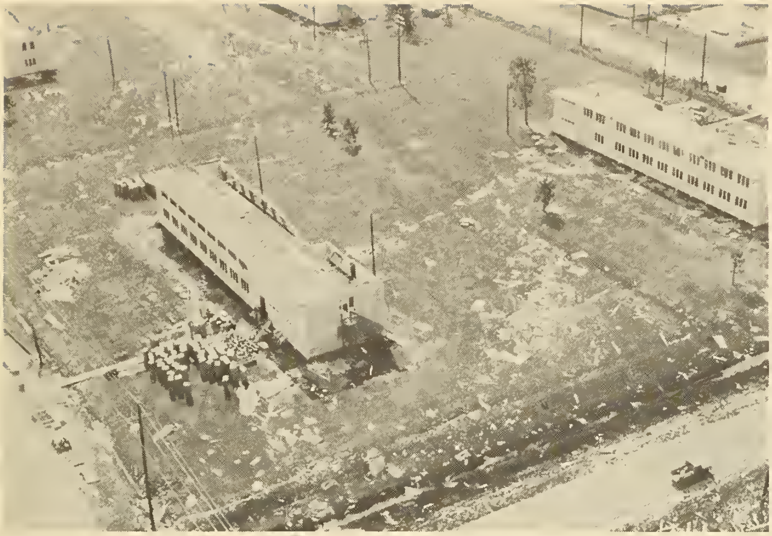
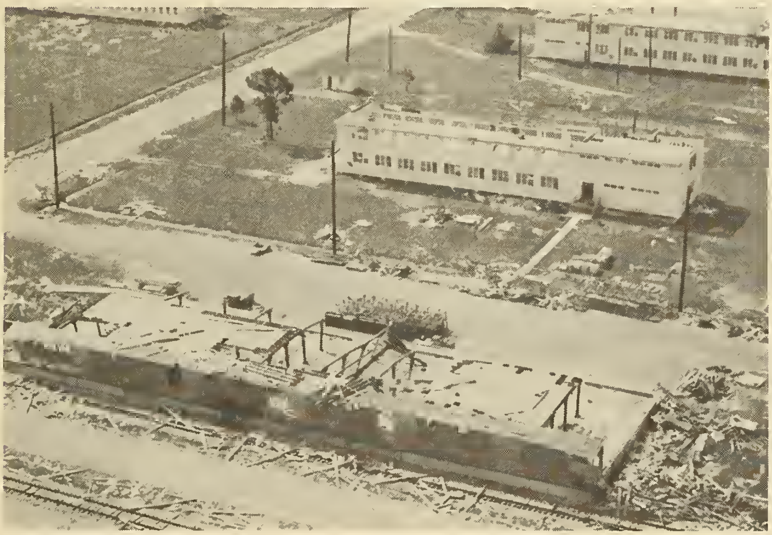


Figure 34. Wood-frame barracks, U.S. Naval C. B. Center, Gulfport.

Figure 35. Wood-frame warehouse and barracks, U.S. Naval C. B. Center, Gulfport, Mississippi.



broken off some distance above the ground (fig. 36).

Figure 37 illustrates a steel-framed building which lost one end-wall and most of its light wood-frame cladding.

A 12-in thick masonry end wall of the new B.O.Q. building was also toppled during the hurricane (fig. 38). The forces causing the outward collapse of this wall were probably due to a combination of suction on the leeward side and a high internal pressure. However, an inspection of the construction indicated there were no metal anchors tying the wall to the adjacent laminated timber arches. Brick masonry columns at both ends of the wall contained vertical steel reinforcement, but this reinforcement extended only about 20 inches above the column base. Underneath the collapsed masonry wall (note hump in fig. 38) is a car which was parked by the owner in what he probably considered to be a sheltered and safe location. Other automobiles at the U.S. Naval Center were also damaged by flying debris (fig. 39).

Figures 40 and 41 indicate the sporadic nature of wind damage in the area west of the U.S. Naval Center and north of Long Beach. Failures were usually initiated by loss of carport roofs or large roof overhangs which often led to removal of the complete roof structure.

The remains of a mobile home in the same general area are shown in figure 42. The areas shown in the figures 40-42 are relatively clear of large trees, a fact which probably reduced the intensity of damage.

Figure 36. U.S. Naval C. B. Center, Gulfport.

Figure 37. U.S. Naval C. B. Center, Gulfport, Mississippi.

Figure 38. Masonry wall damage, U.S. Naval C. B. Center, Gulfport.

Figure 39. Damaged car, U.S. Naval C. B. Center, Gulfport, Mississippi.

Figure 40. Residential area west of Gulfport.

Figure 41. Residential area north of Long Beach, Mississippi.

Figure 42. Remains of mobile home, Long Beach.

Figure 43. Saint Thomas Catholic Church, Long Beach, Mississippi.

Heavy structural damage due to windfalls was observed in many areas.

Long Beach

Long Beach, located between Gulfport and Pass Christian, experienced maximum wind speeds and surge heights of approximately 130 mph (fastest mile) and 21 ft, respectively (fig. 3). As illustrated in the following figures (43-53), many of the buildings along this coastal area were totally destroyed by wave wash.

Figure 43 shows a wood-frame church which was badly damaged by wave action. Commercial buildings located in a shopping center on U.S. Highway 90 are shown in figures 44-46. A small store constructed with masonry walls and located on the coastal side from the supermarket shown in figures 45 and 46 was completely destroyed. The church building shown in the center background of figure 45 had considerable storm surge damage to its interior although its exterior walls and roof were only slightly damaged.

Water-borne debris piled up in front of a damaged masonry veneer wood-frame building (probably a motel) is illustrated in figure 47.

Ramada Inn - This motel (fig. 48) consists of a main building parallel to the highway (U.S. Route 90) plus two wings perpendicular to and behind the main building. As shown in figure 48, the motel wing on the right (east wing) suffered more damage than the other wing, probably because of its clearer exposure to the waves. The main building including

Figure 44. Commercial building, Long Beach. (Building is located across the street from shopping center shown in fig. 45).

Figure 45. Shopping center, Long Beach, Mississippi.

Figure 46. Close-up view of supermarket shown in figure 45.

Figure 47. Close-up view of residential building, Long Beach, Mississippi.

Figure 48. Ramada Inn, Long Beach, Mississippi.

Figure 49. Restaurant area on west end of main building, Ramada Inn, Long Beach.

the restaurant area (fig. 49) experienced extensive water damage. On the east end of the main building, the top-story portion of a masonry wall had collapsed (fig. 50). An inspection of this brick and block wall indicated it contained some vertical reinforcement; however, the block cells containing this reinforcement did not contain any grout or concrete (fig. 51).

Figures 52 and 53 illustrate the total destruction of numerous small residential buildings along the Long Beach and Pass Christian coastal area. The distance which the storm surge traveled inland is also evident in these figures.

Pass Christian

Along the coastal area in Pass Christian, several apartment buildings were totally destroyed by wave action. One of these buildings was the Richelieu Apartments (fig. 54) where 23 persons were killed because they failed to heed warnings to evacuate. A close-up view of the remains of the Richelieu Apartments, a three-story brick veneer and wood-frame building is shown in figure 55.

The remains of other demolished apartment buildings are illustrated in figures 56-58. The construction of these buildings was similar - brick veneer and wood frame.

A residential area of Pass Christian is shown in figure 59. Fallen trees indicate that maximum winds were from the east (fastest mile speeds were probably in excess of 140 mph). The Pass Christian business

Figure 50. Damaged masonry wall on east end of main building, Ramada Inn.

Figure 51. Damaged masonry wall, Ramada Inn; block cells containing vertical reinforcement were not grouted.

Figure 52. Residential area along coast, Long Beach, Mississippi.

Figure 53. Coastal area, Long Beach.

Figure 54. Richelieu Apartments, Pass Christian.

Figure 55. Debris from Richelieu Apartments, Pass Christian, Mississippi.

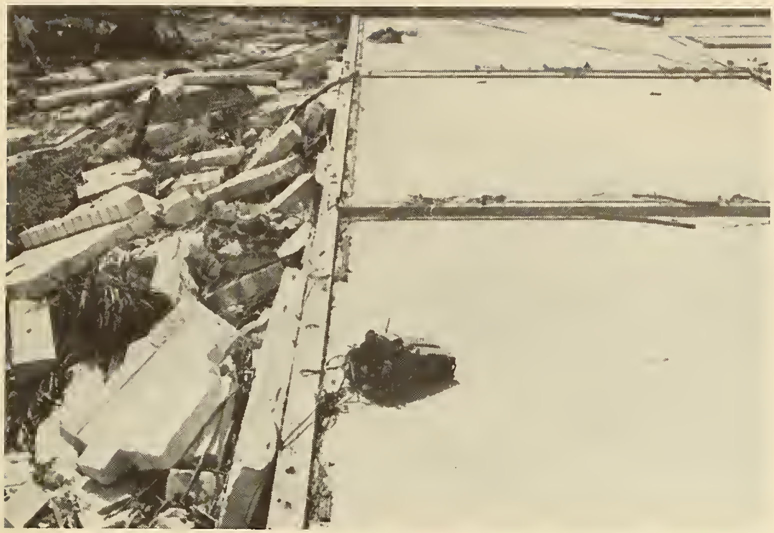


Figure 56. Remains of an apartment building, Pass Christian, Mississippi.

Figure 57. Brick veneer from destroyed apartment building, Pass Christian.

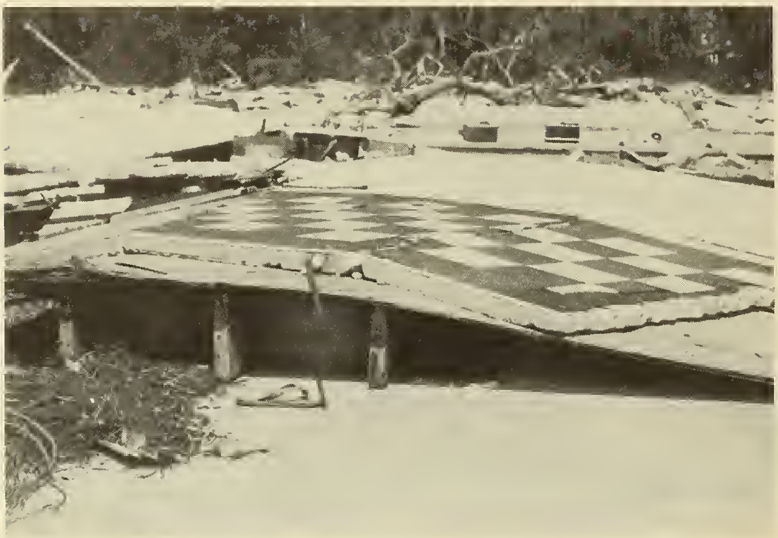


Figure 58. Floor construction used in some apartment buildings, Pass Christian.

Figure 59. Residential area, Pass Christian, Mississippi.

district suffered extensive damage as illustrated in figure 60. The debris in the center of the figure is all that remains of the commercial buildings which were located on the south (near) side of the street. Note U.S. Highway 90 in the foreground. Accumulations of debris were particularly heavy in the back bay areas and along the beaches of Mississippi Sound as indicated in figure 61.

St. Louis Bay Crossings

The L & N Railway Bridge over St. Louis Bay is shown in figure 62. Rails, ties and ballast were swept from the deck by surge-borne waves. The missing span was not carried away in the storm but was severely damaged and required replacement. The bridge carrying U.S. Route 90 (shown in background) suffered damage very similar to that of the Biloxi Bay Bridge. A displaced deck slab is shown in figure 63.

Bay St. Louis

Figures 64 and 65 indicate the intensity of damage in the Bay St. Louis residential area. It is believed that the center or "eye" of Camille passed directly over this portion of the city. Note that most of the trees have been uprooted rather than broken off.

One of a group of modern single-family dwellings near Bay St. Louis, which suffered only minor wind damage, is shown in figure 66. In this and several other dwellings, it was noted that the corner supports for the carports were either slightly damaged or completely destroyed. The wind-resistant asphalt shingles on the houses performed very well.

Figure 60. Business area, Pass Christian, Mississippi.

Figure 61. Debris along east abutment of Bay St. Louis Bridge.

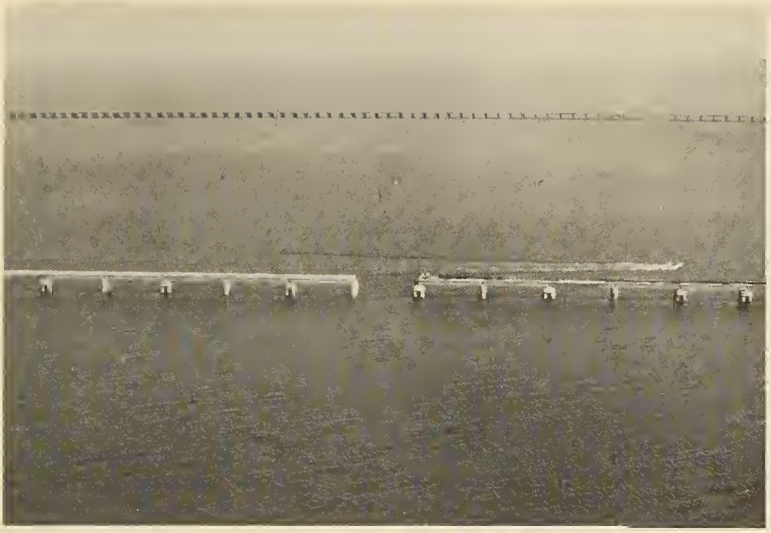


Figure 62. L & N Railway Bridge, Bay St. Louis. (Damaged span removed).

Figure 63. Bay St. Louis Bridge, U.S. Highway 90.

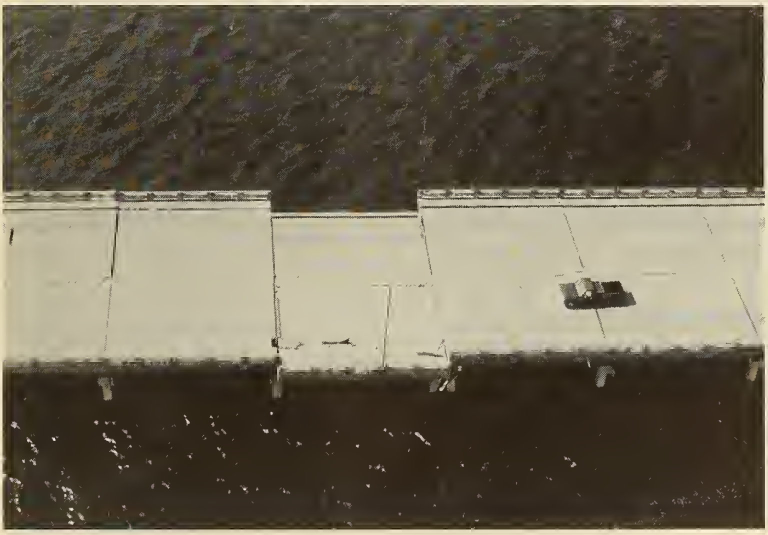


Figure 64. Residential area, Bay St. Louis, Mississippi.

Figure 65. Residential area, Bay St. Louis.

Figure 66. Single-family residence near Bay St. Louis.

Figure 67. Single-family residence, Waveland, Mississippi.

Waveland

A residence and a bank building, which were struck by waves, are illustrated in figures 67 and 68. The residential building lost most of its exterior and interior wall coverings but the good anchorage of the wood-stud walls to the concrete slab foundation and to the timber roof prevented total destruction. As shown in figure 68, the bank building was completely destroyed except for the reinforced concrete vault and building frame.

A small two-story motel located about 3 miles from the coast and on U.S. Route 90 near Waveland, Mississippi, is shown in figure 69. This brick-veneer and wood-frame building was arranged in a U-shaped plan and had a flat roof overhanging the second floor exit balcony. The direction of the wind was such that it resulted in one wing of the motel losing only part of its built-up roofing (fig. 69), while the other motel wing (fig. 70) was stripped of its entire roof structure due to the uplift forces acting on the roof overhang.

Across the highway from the small motel is a larger two-story motel, which has a flat concrete roof overhanging the second-story balcony (fig. 71). In this building the roof structure was apparently heavy enough and anchored satisfactorily to resist the uplift forces. The only damage observed was to the built-up roofing and underlying insulation.

Figure 68. Bank building, Waveland.

Figure 69. Motel near Waveland, Mississippi.

Figure 70. Damaged wing of motel shown in figure 69.

Figure 71. Motel, U.S. Highway 90 near Waveland, Mississippi.

One of the many mobile homes which were overturned is shown in figure 72. This particular mobile home was located in Louisiana on U.S. Route 90 just west of Pearlington, Mississippi.

Hancock County - Inland Area

North Central High School is located on County Road 603 about 15 miles north of Waveland, Mississippi. The main school buildings are constructed with brick and block walls and a steel joist roof system. As shown in figure 73, the roof covering and insulation were stripped from the buildings and the windows were badly damaged. This exterior damage also resulted in extensive rain damage to the interior and contents of the buildings.

Two mobile homes adjacent to the main buildings and used as temporary classrooms were totally destroyed (fig. 74).

A smaller masonry building containing athletic locker rooms lost most of its built-up roof covering (fig. 75). It appeared that the wind probably tore off the roof vents first which then made the roof covering more vulnerable to wind action.

A small concrete block building (fig. 76) near the other school buildings had a wood-frame roof which was adequately anchored to the walls. Wind uplift on the roof did produce some major tensile cracks in the horizontal mortar joints of the walls.

Figure 72. Damaged mobile home, U.S. Highway 90 near Pearlington, Mississippi.

Figure 73. North Central High School between Waveland and Poplarville, Mississippi.

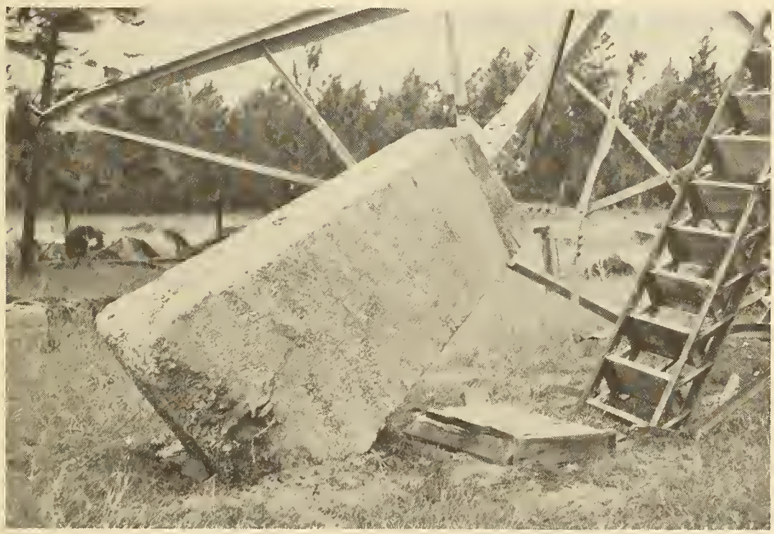
Figure 74. Temporary classrooms, North Central High School.

Figure 75. Athletic building, North Central High School.

About five miles north of the North Central High School, a tall steel observation tower was toppled by the strong winds. One leg of the tower was sufficiently anchored to a concrete footing (fig. 77) to pull the footing from the ground and drag it about 15 ft when the tower overturned.

Figure 76. Small concrete block building, North Central High School.

Figure 77. Steel observation tower near North Central High School.



DISCUSSION

Natural disasters such as Hurricane Camille provide full-scale tests of buildings and other structures. Information gained from the systematic study of building performance in these disasters should lead to improved design and construction practices that will save lives and reduce property losses. In the following discussion, observations relating to wind speed, storm surge and consequent structural damage are briefly summarized.

Wind Speeds

Spectacular estimates of wind speeds have been presented in a number of reports and articles on Hurricane Camille with little consideration given to type of exposure, height of observation and instrument characteristics. In reviewing hurricane reports submitted after the passage of Camille, approximately six observations of wind speed were considered to be reasonably reliable. Most of these required some adjustment to standard height and conversion to fastest mile. This lack of reliable information is quite remarkable considering the advanced warning of the hurricane's path and the number of major installations with wind measuring equipment in the storm area.

In order to evaluate the performance of buildings and other structures along the Mississippi Gulf Coast, the severity of the storm must be compared with accepted design wind speeds. As indicated earlier in this report, the 50-year design winds (95 mph) were exceeded in the area extending from Slidell, Louisiana, to Ocean Springs, Mississippi, while

the 100-year design winds (105 mph) were probably exceeded over the central half of this area. Though the true severity of Camille will never be known, it is interesting to note that the reported design speed of 150 mph assigned to the Mississippi Power Company building corresponds to a mean recurrence interval of approximately 370 years. As noted previously, this structure suffered relatively minor damage.

The number of tornadoes generated during the passage of Camille is unknown. Waterspouts were observed on Keesler AFB radar during the storm and the type of damage observed by the survey team in certain areas suggested tornadic action.

Storm Surge

The storm surge generated by Camille along the Mississippi Gulf Coast was particularly devastating. It is believed that damage directly attributable to wave action and flooding far exceeded that due to wind in the area covered by the survey. Greater consideration should be given to storm surge, a factor which is overlooked in most existing building codes.

The prediction of surge heights is exceptionally difficult because of the number of variables involved. In addition, the design of most buildings to directly resist wave action is generally impractical because of the prodigious loads involved.

In future development of the devastated area, the following steps could substantially reduce the risk of surge damage.

1. Minimize the effects of wave action by leaving ground-floor areas completely open and using this space for plazas and parking.
2. Constructing buildings on elevated areas, as in the case of the Mississippi Power Company building, or on pole or pile supports.
3. Institute restricted zoning in areas known to be vulnerable to storm surge.

Building Damage

Since the NBS team spent only a brief period (approximately 3 days) surveying the damage along the Mississippi Gulf Coast, it was not possible to conduct a detailed inspection of many of the buildings illustrated in this report. Accordingly, the following discussion is based on typical damage which was observed.

Current Design Practice - The satisfactory performance of various major buildings and structures (for example, Broadwater Beach Marina, fig. 11; Mississippi Power Company Building, fig. 19; U.S. Naval Center concrete and masonry warehouses, fig. 32; and motel, fig. 71) indicates that the use of current good design and construction practices can greatly minimize property damage resulting from hurricane winds and storm surge.

In general, wood-frame residential buildings (figs. 10, 25, 27, 66) performed very well where they were constructed in accordance with current recommendations [7, 14, 15]. As demonstrated in Hurricane Camille as well as in previous hurricanes, it is essential that wood-frame buildings be properly anchored to their foundations, and walls, floors and roofs adequately tied together.

The proper use of reinforced masonry walls in many buildings (figs. 31, 38, 45, 50) would probably have reduced some of the damage which was observed.

Roofs - Roof damage on buildings with flat roofs (figs. 13, 32, 33) clearly demonstrates the need to give more consideration to local wind effects. The effect of building geometry on local wind pressures was apparent in a number of cases (figs. 9, 18, 22).

Carport roofs and roof overhangs were particularly vulnerable in a considerable number of residential buildings (figs. 40, 41, 66, 69, 70). In some of these buildings, failures which were initiated by loss of carport roofs or roof overhangs led to removal of the complete roof structure.

Roof Coverings - Wind-resistant (self sealing) asphalt shingles performed very well as shown in figures 10 and 66. Inadequate fastening resulted in metal roofing (figs. 9 and 27) being stripped from some buildings. Built-up roofing applied to concrete roof decks (fig. 32) generally suffered little damage. However, built-up roofing applied over insulation

(regardless of type) appeared to experience more damage (figs. 24 and 75). In a majority of cases, built-up roofing damage appeared to commence at the perimeter of the roof. Lack of adequate perimeter attachment was evident where serious damage was observed. In one building (fig. 75) the loss of roof exhaust vents probably caused the removal of considerable built-up roofing.

Anchorage Details - The lack of proper anchors to connect various building elements together caused damage in at least two buildings (figs. 33 and 38)

Construction Inspection - The lack of adequate inspection during construction was also evident in several damaged buildings. One example of construction deficiencies is shown in figure 51. Additional examples have been presented in other reports [10, 13].

Mobile Homes

The majority of mobile home damage observed (figs. 42, 72, 74) could have been greatly minimized by the use of over-the-roof ties as specified in the current standard for mobile homes [16]. Because the panel connections on mobile homes are not sufficiently ductile, partial failures generally develop into complete failures, making anchors attached only to the floor system less effective. This observation is supported by the statistics presented earlier in this report which show that the ratio of mobile homes destroyed to those with major damage has a trend opposite to that of conventional homes and farm buildings.

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